Received: 1 August 2022 | Accepted: 10 January 2025

DOI: 10.1111/ajae.12532

ARTICLE

Impacts of Sandstorms on Wheat Yield in Northern China

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Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 72322008, 72173004, 72348003, 41971130

Abstract

Sandstorms, exacerbated by global warming and distinct from industrial sources of air pollution, have significant detrimental effects on various socio-economic factors. However, evidence of their impact on agricultural production and the adaptation strategies employed by farmers remains limited. This paper estimates the impacts of sandstorms on crop yields and examines the associated adaptation strategies. Using data from 288 counties in China's winter wheat production regions spanning 2000 to 2007, we uncover a substantial 14.8% reduction in winter wheat yields in northern China due to sandstorms. Each additional hour of sandstorm during the winter wheat growing season corresponds to a 1.4% decrease in yield. Household-level data further reveal that sandstorms not only threaten food security by reducing crop yields, but also lead to a significant decrease in planted areas. Furthermore, we find that farmers increase their investments in fertilizer and labor as adaptation measures to mitigate the negative impacts of sandstorms on crop yields. Our results suggest that timely irrigation following a sandstorm, especially in areas with less precipitation, can effectively mitigate its adverse effects, offering valuable insights for reducing the economic impact of sandstorm events. These findings underscore the need for adaptive strategies to safeguard agricultural productivity in the face of increasing sandstorm risks, offering valuable insights for policymakers and stakeholders engaged in agricultural resilience planning.

KEYWORDS

adaptation, agriculture, China, sandstorm, wheat yield

JEL CLASSIFICATION

Q10, Q54

1 | INTRODUCTION

Agriculture is one of the most vulnerable sectors affected by extreme weather events and human-made pollution. There are two strands of literature that examine the magnitude of the impacts on agricultural production from environmental externalities, though sandstorms are rarely addressed. One strand of literature focuses on climate change, including temperature changes, precipitation variability, and extreme weather events (Deschênes & Greenstone 2007; Lesk et al. 2016; Rojas et al. 2019; Schlenker & Roberts 2009). For instance, historical data indicate that a significant drought event led to a substantial 10% reduction in national cereal production worldwide during the period from 1964 to 2007 (Lesk et al. 2016). Further studies estimate global average annual yield losses attributable to flooding between 1982 and 2016, quantifying reductions of 4% for soybeans, 3% for rice, 2% for wheat, and 1% for maize (Kim et al. 2023). The second strand of literature delves into the impacts of human-made air pollution on crop production, highlighting factors such as ozone and aerosols. To illustrate, research indicates that the cumulative ozone levels surpassing the critical threshold of 40 ppb resulted in an average annual yield reduction of 8% for rice and 6% for wheat across China, in comparison to conditions below the critical levels (Feng et al. 2019). Additionally, scholars have examined the consequences of agricultural damage caused by various natural disasters, including hurricanes (Kunze 2021; Mohan 2017), earthquakes (Slater & Birchall 2022), and volcanic eruptions (Proctor et al. 2018; Wilson et al. 2011).

Sandstorms, driven by global warming and distinct from industrial sources of air pollution, exert detrimental impacts on various socioeconomic factors. A sandstorm, typically prevalent in arid and semiarid regions, is a meteorological phenomenon that occurs when strong surface winds lift substantial amounts of dust from the ground into the air, reducing visibility to less than 1000 m at eye level (UNEP, WMO, & UNCCD 2016). Over the past century, annual dust emissions have risen by 25%–50% worldwide, primarily due to unsustainable land use changes and land degradation, particularly in arid and semiarid areas (WAD 2019).[1] Current research reveals that sandstorms lead to transportation disruptions, traffic accidents, increased incidence of violent crimes and assaults, and adverse impacts on human health. For instance, Middleton et al. (2021) reported a fivefold increase in hospital cases related to motor vehicle collisions during a severe sandstorm in Qatar, primarily due to reduced visibility. In Iran, from 2013 to 2020, 7.5% of total flights were canceled because of sandstorms (Miri & Middleton 2022). Surprisingly, in the U.S., violent crimes and assaults were 12.7% and 14.7% more frequent on days with sandstorms compared to days without (Jones 2022). Moreover, sandstorms adversely affect human health by causing damage to the respiratory and cardiovascular systems (Lwin et al. 2023; Tobias et al. 2019), leading to increased hospitalizations, higher mortality rates, and lower birth weights and premature births (Jones 2022; Sadeghimoghaddam et al. 2021).

While natural scientists have extensively investigated the impact of sandstorms on crop yields and delved into the underlying mechanisms through agronomic field experiments, there remains a paucity of empirical evidence concerning the effects of sandstorms on agricultural production in actual farm settings. For example, Zia-Khan et al. (2014) conducted a field experiment by applying 100 g/m^2 of dust three times at 10-day intervals to a $5m \times 5m$ plot. They found that compared to the control group, the dust composition resulted in a 28% reduction in cotton yield. In another field experiment, Hatami et al. (2017) simulated a sandstorm with a concentration of 1500 $\mu g/m^3$ and found that this simulated sandstorm caused a 35% decrease in grain yield, a 10% decrease in 1000-seed weight, and an 8% decrease in plant height. Results from field experiments provide valuable insights into the impacts and mechanisms of sandstorms on crops, while using large-scale aggregated data allows us to examine the impacts of sandstorms on actual farms and quantify the adaptation effects. Sandstorms not only threaten food security by reducing crop yields but may also lead to a decrease in the planted area, as farmers might choose to cease production to mitigate

[1]World Atlas of Desertification (WAD), 2019. World Atlas of Desertification. Available at: https://wad.jrc.ec.europa.eu/atmosphericdust

potential losses. However, once crops are planted and subsequently exposed to sandstorms, farmers may respond by investing in additional agricultural inputs to counteract yield losses. This raises a critical question: To what extent are these adaptation measures effective in reducing the adverse impacts on crop yields?

This paper examines the effects and associated mechanisms of sandstorms on agricultural production, using winter wheat in China as a case. The majority of global sandstorms originate from 45 countries, with 38 of them situated in Africa and Asia, primarily comprising developing nations with developing agricultural economies and smallholder farms, similar to the case of China. However, the absence of comprehensive sandstorm monitoring data has hindered scholars' understanding of the magnitude of sandstorm impacts on agricultural production. China's extensive monitoring and statistical data offer a valuable opportunity to access the impacts of sandstorms on small-scale farms. Moreover, China's substantial investments in agricultural infrastructure, combined with detailed farm-level data, enable us to explore the effects of *ex-post* adaptation measures following sandstorm occurrences. Notably, China stands as one of the world's most vulnerable nations to sandstorms, having experienced a total of 125 sandstorms between 2000 and 2021, including 35 severe sandstorms (N. Wang et al. 2023). The frequency of sandstorms in northern China has exhibited a fluctuating increase in recent years, partially attributed to rising temperatures and below-average rainfall in its neighboring Mongolia (Piao et al. 2023; Y. Liu et al. 2022).

We find that the occurrence of sandstorms causes a significant 14.8% reduction in winter wheat yield in northern China. In terms of intensity, each additional sandstorm hour during the winter wheat growing season leads to a 1.4% decrease in yield. The impacts of sandstorms vary with their visibility levels; compared with no sandstorms, the yield of winter wheat decreased by 1.1% for each additional hour of less severe sandstorm, and by 1.9% for each additional hour of more severe sandstorm. Moreover, we find that the sandstorms negatively affect winter wheat growth only when the duration of a sandstorm event exceeds four hours, while a sandstorm lasting less than four hours has little effect. In terms of growth stages, winter wheat is more sensitive to sandstorms during its fall (sowing to before overwintering) and winter (overwintering) stages than in the spring (turning green to harvest).

Our mechanism analysis reveals that sandstorm occurrences significantly influence farmers' planting decisions, as suggested by a reduction in the planted area of winter wheat to avoid potential losses. Specifically, sandstorms in the previous year led to a 1.4% reduction in the planted area of winter wheat in the current season compared to periods without sandstorms. Additionally, our results show that sandstorms lead to an increase in agricultural input use, with per-hectare fertilizer costs rising by 12.7% and labor days increasing by 8.0% compared to nonsandstorm periods. These increased agricultural inputs significantly mitigate crop yield losses. Furthermore, timely irrigation following a sandstorm proves effective in mitigating its detrimental effects, especially in regions with lower precipitation levels.

This paper makes two significant contributions to the existing literature. First, it provides additional evidence regarding the often-overlooked environmental externality of sandstorms and their impact on crop production. This is achieved through a unique large-scale dataset and a comprehensive evaluation of sandstorm effects on crop yield. Two studies are closely related to our research. Ahmadzai et al. (2023), using cross-sectional household survey data, identified a 3% decline in crop value resulting from an additional sandstorm, with each extra day of sandstorm exposure reducing wheat yield by 24%. Our study builds on Ahmadzai et al. (2023) by introducing a more diversified set of sandstorm indicators. Whereas Ahmadzai et al. (2023) measured sandstorm effects by events and days, our approach includes sandstorm hours, severity, and stages, enabling a more precise assessment of their impacts. In contrast, Gholizadeh et al. (2021) employed sandstorm hours as a key measure, but focused solely on the impact on farm income, using data from 16 counties in Iran. They found that each additional hour of dust occurrence reduced the income of barley farmers by 0.08–0.36 USD/ha based on a Ricardian model. Unlike Gholizadeh et al. (2021), our access to detailed sandstorm monitoring and county-level panel data enables us to examine the impacts of sandstorms on winter wheat yield, considering variations in visibility, duration, and crop season. Additionally, we find that sandstorm occurrences also lead to a reduction of 1.4% in the planted area of winter wheat, suggesting that sandstorms threaten food security both intensively (yield) and extensively (planted area).

Second, our results highlight the importance of *ex-post* adaptation measures in mitigating the adverse impacts of sandstorms on crop production. While existing studies have evaluated the effectiveness of *ex-ante* sandstorm control measures in China—such as the Three-North Shelterbelt Project (Tan & Li 2015; Wang et al. 2010) and the Beijing-Tianjin Sand Source Control Project (Jiang et al. 2018; Qin et al. 2012)—they have shown that while such measures are effective, their impact remains limited. Given the constrained role of *ex-ante* measures and the increasing frequency of sandstorms, there is greater value in exploring effective strategies to mitigate agricultural damage after sandstorms occur. Our analysis demonstrates that farmers' adaptation measures play a crucial role in reducing the negative effects of sandstorms on crop yields. Specifically, farmers increase investments in fertilizer and labor to minimize crop losses. Moreover, timely irrigation following a sandstorm can significantly mitigate the negative effects, particularly in regions with low precipitation. These findings offer valuable insights for reducing the economic costs associated with sandstorm events.

The remainder of the paper is organized as follows. Section 2 provides the background of this paper. Sections 3 and 4 present data and empirical strategy, respectively. Sections 5 and 6 present the basic results and the results from mechanism analysis, respectively. Section 7 discusses and concludes the paper.

2 | BACKGROUND

Sandstorms, meteorological events characterized by the suspension of substantial quantities of sand and dust particles in the atmosphere due to strong surface winds, pose a significant global environmental concern. These occurrences are most prevalent in arid and semiarid regions, with prominent sources including Northern Africa, the Arabian Peninsula, Central Asia, and China (World Meteorological Organization (WMO) 2020). Ongoing climate change plays a pivotal role in this escalation, as rising temperatures and shifting precipitation patterns exacerbate desertification in various regions, leading to an increased frequency and intensity of sandstorms (Wu et al. 2021). Dust particles are acknowledged as major contributors to atmospheric particulate matter on a global scale, accounting for an estimated 40% of aerosol concentrations in the troposphere (WMO 2015) They transport substantial quantities of particulate matter aloft, impacting air quality and traveling hundreds to thousands of kilometers before settling (Goudie 2014). Sandstorms result in significant socioeconomic consequences by causing damage to crops and infrastructure, as well as posing threats to human health and traffic safety due to poor air quality (United Nations Convention to Combat Desertification (UNCCD) 2022a). Given the long-range dispersion characteristics of sandstorms, approximately 334 million people across 151 countries, constituting 77% of the global population, are affected by these phenomena (UNCCD 2022b).

Given their profound implications for the environment, public health, agriculture, livelihoods, and overall socioeconomic well-being, sandstorms have emerged as a critical global concern that has prompted extensive global efforts in recent decades. In response to these challenges, a series of comprehensive global initiatives have been launched. One prominent policy endeavor is the United Nations Convention to Combat Desertification (UNCCD), which acknowledges the gravity of sandstorms and their association with desertification and land degradation processes. The UNCCD promotes a three-pronged approach to tackle sandstorms, emphasizing early warning systems, preparedness and resilience measures, and the mitigation of anthropogenic sources (Zucca et al. 2021). Furthermore, organizations such as the United Nations Environment Programme (UNEP) have played a leading role in recognizing the significance of sandstorms. In 2016, UNEP, in collaboration with partners, released the world's inaugural comprehensive assessment of sandstorms. This assessment meticulously identifies dust sources, outlines key trends, and furnishes specific policy recommendations to mitigate the impacts of sandstorms. To further advance these endeavors, the Coalition to Combat Sand and Dust Storms was established in 2018, with the aim of facilitating effective strategies for combating sandstorms and fostering coordination among both United Nations and non-United Nations stakeholders. In acknowledgment of the imperative of international cooperation in addressing this issue, the United Nations General Assembly adopted a resolution designating 12 July as the International Day to Combat Sand and Dust Storms, underscoring the global commitment to raise awareness and mobilize collaborative actions to address the challenges posed by sandstorms on an international scale.

China ranks among the countries most severely impacted by sandstorms worldwide, particularly in the northern regions where heavy sandstorms are common occurrences during the spring season. These conditions are exacerbated by factors such as deforestation and rising regional temperatures (Zhang et al. 2020). Sandstorms in China stem from diverse sources, comprising both domestic and transboundary contributors. Domestically, the issue is exacerbated by extensive land degradation and desertification. In 2019, the total area of desertified land in China reached 2.57 million square km, accounting for 26.81% of the country's landmass and serving as a substantial source of sandstorms. Additionally, Mongolia has emerged as the predominant overseas source area, contributing to 70% of the sandstorms affecting China (Zhang and Gao 2007). The combined contributions of sand and dust from these sources have led to frequent sandstorms in China, resulting in significant economic and environmental damage. An illustrative example of the impact of these sandstorms is the severe event in March 2021, which swept across 45 million hectares of land in 12 northern Chinese provinces, causing a substantial increase in PM_{10} concentrations in Beijing, exceeding 8000 μg/m^3, and resulting in a direct economic loss surpassing 30 million yuan (Filonchyk 2022; Yin et al. 2022). The seriousness of the issue is further emphasized by the events in 2023, with China experiencing 12 dust events as of April 30, marking the highest frequency observed in nearly a decade (Chen, Zhao, et al. 2023).

In response to the pressing issues of desertification and the adverse impacts of sandstorms, the Chinese government has undertaken a dedicated effort to combat desertification and enhance ecological resilience. In 1978, China initiated the world's most extensive afforestation program, known as the Three-North Shelter Forest Project. Encompassing 551 counties across 13 provinces in China's arid and semiarid regions, this project focuses on conserving soil and water resources and curbing land degradation through large-scale afforestation (Li et al. 2023). Subsequently, the Chinese government introduced a series of complementary initiatives, including the Natural Forest Conservation Program (NFCP) (Liu et al. 2008), the Grain for Green Program (GGP) (Song et al. 2014), and the Beijing-Tianjin Sand Source Control Program (Wu et al. 2013). These programs are designed to combat wind erosion, stabilize sand-prone areas, and establish green ecological barriers by returning farmland to forests and grasslands, prohibiting reclamation and grazing, and promoting afforestation. Since 1978, China has consistently executed a range of substantial ecological projects that remain ongoing, with a total investment exceeding 1.7 trillion yuan (Cai et al. 2020). Among these initiatives, the forest coverage rate within the Three-North Shelter Forest Project area has notably increased from 5% in 1997 to its current level of 13.6%. While significant progress has been achieved in recent years, with a reduction in desertification and an expansion of vegetation cover, substantial deserts and Gobi regions within both domestic and Mongolian territories continue to act as significant and persistent sources of sandstorms in China (Zastrow 2019). Consequently, the challenge of preventing and controlling sandstorms remains a long-term, formidable endeavor, requiring sustained efforts and innovative strategies.

Sandstorms, as sudden meteorological disasters, exert substantial adverse effects on agricultural production, including crop damage, topsoil erosion, infrastructure degradation, and exacerbation of drought conditions (Middleton 2024a). These impacts often exceed the mitigative capacity of preventive measures (Eleftheriou et al. 2023; Opp et al. 2021). To address sandstorm-induced damage,

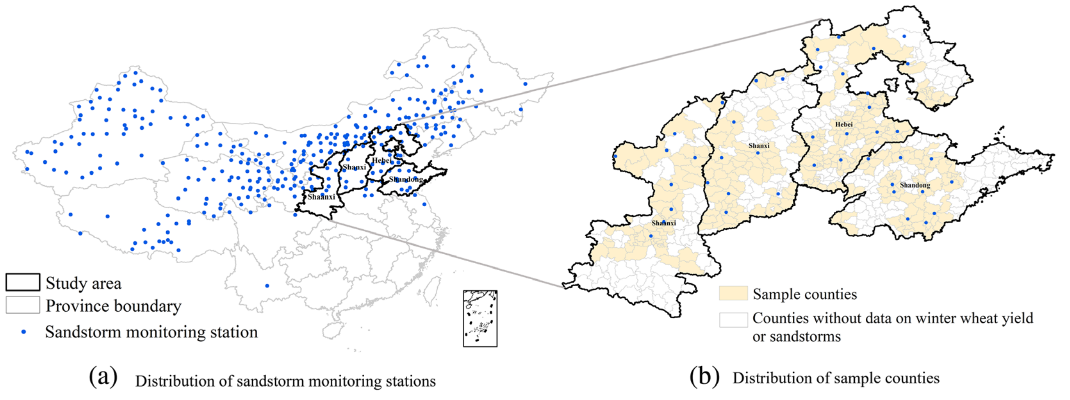

FIGURE 1 The distribution of sandstorm monitoring stations and sample counties.

farmers may adopt post-event adaptation strategies such as adjusting cropping patterns. For example, farmers in Mongolia have abandoned previously productive farmland to minimize income losses resulting from declines in crop yields and productivity due to recurring sandstorms (Ahmadzai et al. 2023). Another adaptation strategy involves modifying production practices, such as increasing the application of fertilizers and agrochemicals, reallocating water resources for irrigation, or cultivating drought-resistant crops (FAO 2023; Qi et al. 2006; Zucca et al. 2021). Additionally, the UNCCD underscores the efficacy of wetting crops to remove sand and dust residues after sandstorm events, which can significantly mitigate their detrimental effects.[2]

3 | DATA

To examine the effects of sandstorms on wheat yield, we construct a unique county-level panel dataset comprising 288 counties across four provinces in Northern China from 2000 to 2007. This dataset includes information on sandstorm occurrence, winter wheat yield, and weather conditions. Figure 1 illustrates the geographical distribution of sandstorm monitoring stations (Panel A) and the selected sample counties (Panel B). To further examine the mechanisms and adaptation effects of farm inputs, we also incorporate a comprehensive farm-level panel dataset comprising 1252 households across four provinces from 2003 to 2007.

3.1 | Sandstorm data

The sandstorm monitoring data utilized herein originated from the China Meteorological Science Data Center (CMDC). This dataset reports detailed sandstorm information for each monitoring station, including sandstorm occurrence date, start and end hours, wind speed, and visibility level of each sandstorm. We have sandstorm data for 278 stations across the whole country from 2000 to 2007. The latitude and longitude information of each monitoring station allows us to match the sandstorm data with the county-level agricultural production data. Consistent with established methodologies in meteorological data matching (Lu & Wong 2008), we use the inverse-distance weighting (IDW) method to assign sandstorm data to each county. Each county takes the value of the weighted average of all monitoring stations within a certain radius of the centroid of that county. We use

[2]UNCCD. Sand and Dust Storms Toolbox-Impact mitigation. Available at: https://www.unccd.int/land-and-life/sand-and-dust-storms/toolbox/impact-mitigation

50 km as the threshold radius and apply inverse distance squared as the weight. After matching with winter wheat yield data, we finally obtain 2224 observations encompassing 228 counties in four provinces from 2000 to 2007. For robustness checks, we also use samples from counties with sandstorm monitoring stations, as well as samples located within 75 km matching radius, respectively.

Based on the raw data, we construct four indicators to measure sandstorms over the whole winter wheat growing season and at each crop stage (i.e., the fall, winter, and spring stages). We first use a binary variable to indicate whether any sandstorms occurred during the winter wheat growing season or at any crop stage. Then, we use the cumulative sandstorm hours during the growing season/stage to indicate the sandstorm magnitude, as existing studies have shown that the extent of crop damage caused by sandstorms depends on the duration of the sandstorm (Sivakumar 2005). Thirdly, we use sandstorm hours at different visibility levels to measure sandstorm magnitude, considering the differences in sandstorm intensity. Specifically, sandstorms can be divided into less severe sandstorms (200 m ≤ visibility <1000 m) and more severe sandstorms (visibility <200 m) (Akhlaq et al. 2012). Finally, we use the number of days with different sandstorm durations (hours) to examine the nonlinearity of the relationship between sandstorm duration and crop yield (i.e., to determine whether sandstorms have a greater impact on crops that experience longer sandstorm hours). Specifically, we count the number of days with different durations during the entire growing season and in each crop stage. That is, sandstorm days with a duration less than 2 h, sandstorm days with a duration less than 4 h but equal to or above 2 h, sandstorm days with a duration less than 6 h but equal to or above 4 h, and sandstorm days lasting equal to or more than 6 h.

Figure 2 illustrates the widespread occurrence of sandstorms, with notable variation across years. On average, 11.5% of the sample counties experienced sandstorms during the winter wheat growing season throughout the study period. There is considerable year-to-year variation: Approximately one-third of counties experienced sandstorms in 2000, while only 2% of counties were affected in

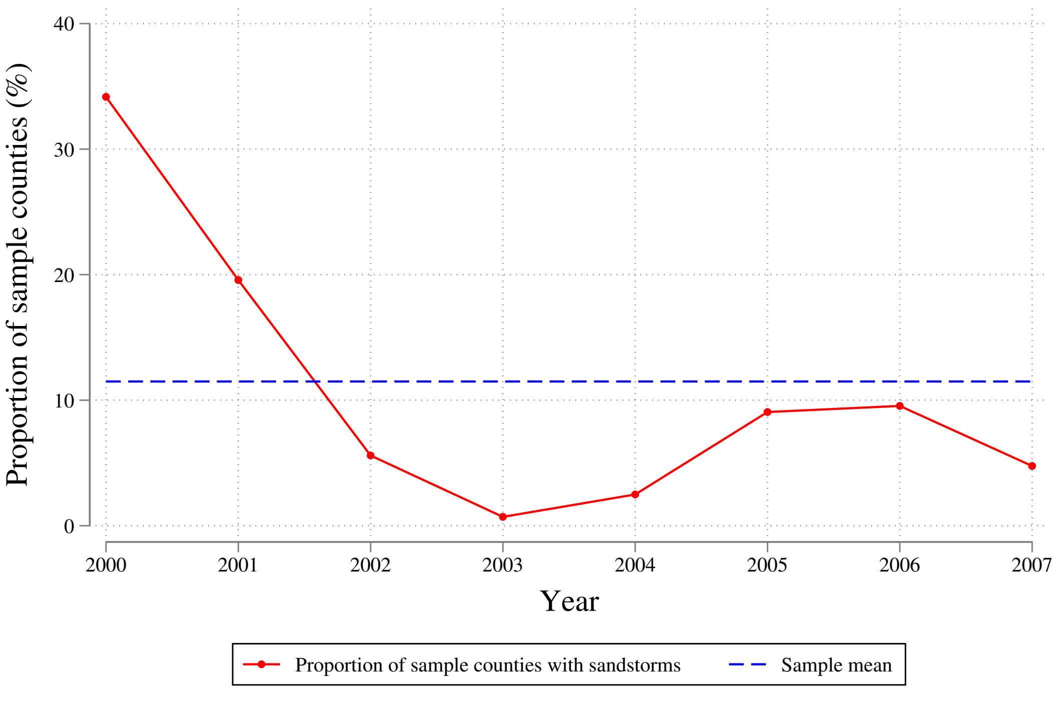

FIGURE 2 Annual variations in the proportion of sample counties with sandstorms. The figure is based on data from sandstorm monitoring stations in sample counties. The proportion is defined as the percentage of sample counties where sandstorms occurred during the winter wheat growing season, relative to the total number of sample counties.

2003. In counties where sandstorms occurred, the cumulative sandstorm hours during the winter wheat growing season averaged 6 h, with the highest recorded at over 22 h in 2002 (Figure A1). Regarding intensity (Figure A2), the majority of sandstorms in the sample counties were relatively mild. However, in 2000 and 2006, the proportion of more severe sandstorms exceeded that of less severe sandstorms. Figure A3 shows that more than half (58%) of the sandstorm days lasted less than 2 h in the sample counties during the winter wheat growing season. Notably, in 2002, a larger proportion of sandstorm days lasted longer than 2 h.

3.2 | Winter wheat production data

The county-level crop production data utilized herein are obtained from the County-Level Agricultural Database provided by the Ministry of Agriculture and Rural Affairs of China. This dataset has been widely used in the literature to study the impacts of climate change on crop yields and agricultural productivity in China (Chen et al. 2016; Chen, Cui, & Gao 2023; Chen & Gong 2021; Zhang et al. 2017). In this study, we focus on winter wheat, as the growing season of winter wheat coincides with that of sandstorms. As this dataset could not differentiate total output between winter wheat and spring wheat, we keep the four provinces—i.e., Hebei, Shaanxi, Shanxi, and Shandong—which exclusively produce winter wheat rather than both types. Collectively, these four provinces accounted for approximately 35% of the country's wheat production in 2018 (National Bureau of Statistics of China, 2018). The major outcome variable of interest is winter wheat yield, which is calculated by dividing winter wheat output by its planted area in each county. To exclude the influence of outliers, we applied winsorization to crop yield at the 1st and 99th percentiles (Li et al. 2014). After excluding missing data and outliers, we end up with 3948 observations for 506 counties from 2000 to 2007 on winter wheat yield.

To assess the effects of sandstorms at different stages of crop growth, we obtained information on planting and harvest dates from the Ministry of Agriculture and Rural Affairs of China. Following the methodologies of Zhu et al. (2022) and Tack et al. (2015), we divide the growing season of winter wheat into three stages, that is, fall, winter, and spring. The fall stage spans from sowing until the end of November, just prior to overwintering. The winter stage covers the overwintering period, from December to February of the following year. The spring stage begins in March when winter wheat begins to green and continues until harvest.

To analyze the mechanisms by which sandstorms affect winter wheat yield, we construct a comprehensive household-level panel dataset derived from the National Rural Fixed Observation Point Survey (NRFOP). Initiated in 1986 by the Ministry of Agriculture and Rural Affairs of China, the NRFOP is the largest long-term follow-up household survey in the country. Due to its extensive coverage, representativeness, and historical depth, this dataset has been widely used in academic research (Benjamin et al. 2005; Gao et al. 2021; Huang et al. 2024). By merging this survey data with the sandstorm information, this study uses data from 1252 households across 25 counties in four provinces, covering the years 2003 to 2007. We obtain the planted area and total output of winter wheat from farmers, where winter wheat yield at the household level is calculated by dividing total winter wheat output by the planted area. The dataset allows us to examine the adaptation effects of four inputs—seed, fertilizer, labor, and machinery—in mitigating yield loss due to sandstorms. The costs associated with each input (e.g., seed, fertilizer, labor in days, and machinery operation) are also collected, as well as the total amount of each input required by farmers to cultivate winter wheat.

Due to data limitations, measuring the impact of irrigation at the farm household level is not feasible. Consequently, we employ county-level data to assess the role of irrigation conditions in mitigating the impacts of sandstorms. The County-Level Agricultural Database provides data on the total irrigated area, defined as the area equipped with irrigation infrastructure or equipment capable of regular irrigation during the current year. To evaluate irrigation conditions, we calculate the irrigation ratio for each county by dividing the total irrigated area by the total planted area.

3.3 | Other data

To separate the effects of sandstorms from other confounding factors, we also collect data on weather conditions. The weather data utilized herein are derived from the China Meteorological Data Sharing Center (CMDC). This dataset contains weather information recorded on a daily basis from 2000 to 2007 for 820 weather stations in China, including minimum, maximum, and average temperature, precipitation, air pressure, relative humidity, and wind speed. Using daily temperature data, we construct a series of weather control variables split into different crop stages (i.e., the fall, winter, and spring stages). For temperature, we use the growing degree days (GDD), defined as the number of degree days within a certain temperature threshold range during each crop stage, to measure. We use three types of GDD to capture the impacts of temperature: GDD_{low}, GDD_{med}, and GDD_{high} (Zhu et al. 2022). Specifically, GDD_{low} is defined as the number of growing degree days at 0–10°C, GDD_{med} for 10–17°C, and GDD_{high} for temperatures greater than 17°C. We measured wind speed, relative humidity, and air pressure by taking the averages during different crop stages, while we measured precipitation and sunshine hours through cumulative values.

Using the geographic coordinate information of the weather stations, we match the weather data to each sample county. Following existing research (Chen & Gong 2021; Zhang, Zhang, & Chen 2017; Deschênes & Greenstone 2007), we use the inverse-distance weighting (IDW) method to match the 115 weather stations with the 288 counties. Each county takes the value of the weighted average of all weather stations within a certain radius of the centroid of that county. We use 200 km as the threshold radius and inverse distance square as the weight.

The summary statistics of all the variables are presented in Table 1 (key variables) and Table A1. The final county-level sample consists of 2224 observations covering 228 counties from 2000 to

TABLE 1 Summary statistics of yield and sandstorm variables.

Variable	Unit	Obs.	Mean	Std	Min	Max
Panel A: County-level data from 2000 to 2007						
Wheat yield	ton/hectare	2224	4.03	2.08	0.24	13.05
Whether sandstorm occurs during growing season	yes = 1, no = 0	2224	0.11	0.31	0.00	1.00
Sandstorm hours in growing season	hours	2224	0.49	3.57	0.00	70.63
Sandstorm hours of common sandstorm	hours	2224	0.27	2.36	0.00	40.79
Sandstorm hours of severe sandstorm	hours	2224	0.22	1.64	0.00	41.67
Panel B: Household-level data from 2003 to 2007						
Winter wheat yield	ton/hectare	4998	4.48	1.77	0.25	11.02
Winter wheat output	ton	4998	1.04	0.83	0.00	25.50
Winter wheat area	hectare	4998	0.25	0.17	0.01	3.69
Seed cost per hectare	yuan/hectare	4998	76.90	177.65	0.00	500.00
Fertilizer cost per hectare	yuan/hectare	4991	1556.25	913.23	0.00	5802.84
Machinery cost per hectare	yuan/hectare	4454	819.60	489.16	0.00	2902.19
Labor days per hectare	days/ hectare	4527	210.42	178.70	0.00	1000.00
Arable land area	hectare	4988	0.47	0.38	0.00	3.33
Total planted area of grain crops	hectare	4998	0.54	0.38	0.03	7.27

2007. The final household-level sample includes 4998 observations covering 1252 households across four provinces from 2003 to 2007.

4 | EMPIRICAL STRATEGY

Our identification strategy relies on the assumption that after including a set of controls for weather conditions and two-dimensional fixed effects, no unobservable variables remain that are correlated with sandstorm activity and winter wheat growth. Following the existing literature (Ahmadzai et al. 2023; Gholizadeh et al. 2021; Jones 2022), we treat sandstorms as an exogenous variable for two reasons. First, in the existing studies, scholars often treat sandstorms as meteorological hazards rather than human-caused events (Arthi 2018; Javadian et al. 2019; Jones 2022; Middleton et al. 2019). Three conditions must be met simultaneously to generate a sandstorm: a source of sand and dust, strong winds, and an unstable atmospheric structure (Rayegani et al. 2020). Obviously, both strong winds and the stability of the atmospheric structure have little correlation with human behavior, as they depend on meteorological features such as regional cyclones (Li et al. 2021; Wyrwoll et al. 2016). Although human activities, such as overgrazing or deforestation, may generate sand and dust (i.e., the source of sandstorms), the process of desertification is very slow and long. One possible concern is that sandstorm control policies may simultaneously affect sandstorms and agricultural production. However, the major objectives of China's sandstorm control policies were to improve the ecological environment and reduce natural disasters, while little attention was paid directly to agricultural production. Second, about 2/3 of sandstorms in China originated from other countries rather than domestically (China Meteorological Administration 2010[3]); this fact reduces the concern that China's efforts to combat sandstorms may induce the endogeneity of sandstorms as the sandstorm control policies may simultaneously affect sandstorms and agricultural production.

We construct the following empirical model to estimate the impacts of sandstorms on wheat yield:

$$\log Y_{i,t} = \alpha_1 Sand_{i,t} + \alpha_2 Wind_{i,t} + \alpha_3 GDD_{i,t} + \alpha_4 W_{i,t} + c_i + \lambda_t + \varepsilon_{i,t} \tag{1}$$

where $logY_{i,t}$ denotes the logarithm of the winter wheat yield in county i and year t. We use $Sand_{i,t}$ to denote different measurements of sandstorms as stated in the data section. These measurements include (1) a dummy variable indicating whether a sandstorm occurred during the winter wheat growing season; (2) the cumulative sandstorm hours during the winter wheat growing season; and (3) the number of sandstorm hours categorized by different levels of visibility; (4) the number of days with different durations during winter wheat growing season (i.e., sandstorm days with a duration less than 2 h, sandstorm days with a duration less than 4 h but equal to or above 2 h, sandstorm days with a duration less than 6 h but equal to or above 4 h, and sandstorm days lasting equal to or more than 6 h).

We control for wind speed, temperature, and other weather conditions because climate conditions may affect both crop growth and sandstorm occurrence (Wang et al. 2022; Chen, Chen, & Xu 2016; Schlenker & Roberts 2009). All of these weather variables are measured in three different crop stages, i.e., spring, fall, and winter, as defined in the data section. We use $\mathrm{Wind}_{i,t}$ to denote the average wind speed. Considering the nonlinear response of winter wheat yield to different temperature exposures, we use $\mathrm{GDD}_{i,t}$, which contains GDD_{low}, GDD_{med}, and GDD_{high}, to capture the impacts of temperature on winter wheat yield. $W_{i,t}$ denotes other weather conditions, including cumulative precipitation, cumulative sunshine hours, average relative humidity, and average air pressure.

We also control for county and year fixed effects. The county fixed effects, c_i, capture the factors that affect both sandstorm occurrence and wheat yield but do not change over time within a county, such as land terrains. We use the year fixed effects, λ_t, to control for the temporally varying shocks

[3]China Meteorological Administration, 2010. The sources and paths of sandstorms. Available at: https://www.gov.cn/govweb/fwxx/kp/2010-03/22/content_1561851.htm

that are common to all counties, such as changes in agricultural technologies and policies during the sample period. The term $\varepsilon_{i,t}$ denotes the error term. The standard errors are clustered at county level to address potential correlations between years within a county.

To further explore the sensitivity of sandstorm impacts on winter wheat at different growth stages, we expanded the model as follows:

$$\log Y_{i,t} = \beta_1 GS1_{i,t} + \beta_2 GS2_{i,t} + \beta_3 GS3_{i,t} + \beta_4 Wind_{i,t} + \beta_5 GDD_{i,t} + \beta_6 W_{i,t} + c_i + \lambda_t + \varepsilon_{i,t} \tag{2}$$

In Equation (2), the terms $\mathrm{GS1}_{\mathrm{i,t}}$, $\mathrm{GS2}_{\mathrm{i,t}}$ and $\mathrm{GS3}_{\mathrm{i,t}}$ represent the sandstorm measurements at the fall, winter, and spring stages, respectively. In this model, we use the sandstorm hours to measure sandstorms. All other indicators and specifications are the same as those described in Equation (1).

To evaluate the effects of sandstorms on planted area and production inputs, we construct the following model using household-level data:

$$\log A_{h,i,t} = \alpha_1 Sand_{\mathrm{i,t}} + \alpha_2 Wind_{i,t} + \alpha_3 GDD_{i,t} + \alpha_4 W_{i,t} + \alpha_5 H_{h,i,t} + c_h + \lambda_{p,t} + \varepsilon_{h,i,t} \tag{3}$$

When analyzing the impact of sandstorms on planted area, $\log A_{h,i,t}$ represents the logarithm of the winter wheat planted area for household h in county i during year t. In examining the impact of sandstorms on production inputs, $A_{h,i,t}$ is a vector of production inputs, including seed cost, fertilizer cost, labor days, and machinery cost per hectare. $Sand_{i,t}$ denotes various measurements of sandstorms, as specified in the Equation (1). We use $\mathrm{Wind}_{\mathrm{i,t}}$, $\mathrm{GDD}_{\mathrm{i,t}}$, and $W_{i,t}$ to represent the average wind speed, temperature exposure, and other weather conditions during the growing season, respectively. $H_{h,i,t}$ represents the household-level controls, including the total arable land area and the total planted area of grain crops. Household-level fixed effects, c_h, are included to control for factors affecting wheat production that remain constant over time within a household. The province-year fixed effects, $\lambda_{p,t}$, control for temporal shocks common to all households within the same province. Finally, $\varepsilon_{h,i,t}$ represents the error terms, which are clustered at the household level to account for potential correlations between years within the same household.

To examine the mitigating effects of agricultural inputs, we introduce interaction terms between sandstorm exposure and agricultural inputs into the model, following the established methodology in the literature (Hill et al. 2024; He et al. 2024; D. Wang et al. 2024; Won et al. 2024), as specified below:

$$\begin{aligned} \log Y_{h,i,t} = {} & \alpha_1 Sand_{\mathrm{i,t}} + \alpha_2 Sand_{i,t} \times Inputs_{h,i,t} + \alpha_3 Inputs_{h,i,t} + \alpha_4 Wind_{i,t} \\ & + \alpha_5 GDD_{i,t} + \alpha_6 W_{i,t} + \alpha_7 H_{h,i,t} + c_h + \lambda_{p,t} + \varepsilon_{i,t} \end{aligned} \tag{4}$$

where $logY_{h,i,t}$ denotes the logarithm of the winter wheat yield for household h in county i and year t. $Inputs_{h,i,t}$ is a vector of inputs that includes seed cost, fertilizer cost, labor days and machinery cost per hectare for household h in county i and year t. The interaction terms between the sandstorm variables and agricultural inputs are included to estimate the adaptive effects of these inputs on mitigating the impact of sandstorms. Our hypothesis is that the coefficients for the interaction terms α_2 will be positive, which suggests that increased input use helps reduce the yield loss of winter wheat caused by sandstorms. All other variables and specifications are consistent with those presented in Equation (3).

5 | BASIC RESULTS

5.1 | Effects of sandstorms on wheat yield

We first examine the impacts of sandstorm occurrence and sandstorm hours on winter wheat yield. Table 2 shows that sandstorm occurrence negatively and significantly affects winter wheat yield. In column (1), the estimation is reported without controls, while column (2) includes weather variables. After accounting for weather conditions, the results in column (2) indicate that sandstorm occurrence significantly reduces wheat yield by 14.8%. Specifically, if winter wheat experiences a sandstorm during the growing season, its yield is, on average, reduced by 14.8%. This corresponds to an approximate yield loss of 596 kg per hectare. These findings are consistent with the results of Shahsavani et al. (2011), who observed that exposure to airborne dust particles at concentrations of 200 $\mu g/m^3$ over five months caused a significant yield loss ranging from 3% to 30%.

We also find that the negative impact of sandstorms on winter wheat becomes more pronounced as the duration of sandstorm exposure lengthens. Columns (3)–(4) report the estimated coefficients of sandstorm hours under different conditions: without any control variables, and with weather variables as controls, respectively. Using sandstorm hours as an indicator, our findings demonstrate that one additional hour of exposure to sandstorms during the winter wheat growing season results in a 1.4% decrease in yield (Col. (3) of Table 2), and the negative impact of increased sandstorm hours is consistent after adding the weather variables (Col. (4)). We also report the results from using the sandstorm days as an alternative in Table A2 in the appendix, which indicates that on average an additional sandstorm day will lead to a 4.4% decrease in the winter wheat yield.

We then examine the sandstorm impacts with different visibility levels and at different crop stages. As shown in column (1) of Table 3, we find that sandstorms with visibility less than 200 m exert a more pronounced impact on winter wheat yields compared to those with visibility ranging from 200 to 1000 m. Compared to no sandstorms, the yield of winter wheat decreased by 1.1% for each additional hour of less severe sandstorm (visibility between 200 m and 1000 m), and by 1.9% for each additional hour of more severe sandstorm (visibility < 200 m). Moreover, our results indicate that winter wheat is particularly sensitive to sandstorms during the fall (from sowing to just before overwintering) and the winter (overwintering) seasons. As column (2) in Table 3 shows, one additional sandstorm hour in the fall and winter reduces the wheat yield by 19.5% and 8.7%. The increase in the number of sandstorm hours in spring will also cause a reduction in the yield of winter wheat, but the impact is relatively small and only 1.1%. This result is supported by Singh et al. (2018) and Stefanski & Sivakumar (2009), who found that winter wheat in the vegetative phase (before the jointing period after regreen) is more susceptible to environmental effects than wheat in the reproductive stage due to the fragility of seedlings.

We further examine the nonlinear impacts of sandstorm hours on winter wheat. The results show that sandstorms have a significant negative effect on wheat yields only when they last for more than four hours. As Figure 3 shows, compared with no sandstorm occurring during the winter wheat

TABLE 2 The impacts of sandstorms on winter wheat yield.

Variables	(1)	(2)	(3)	(4)
Sandstorm occurrence	−0.089**	−0.148***		
	(0.042)	(0.042)		
Sandstorm hours			−0.014***	−0.014***
			(0.005)	(0.004)
Weather controls	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
R-squared	0.680	0.700	0.682	0.700
Observations	2224	2224	2224	2224

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. The standard errors shown in parentheses are clustered at county level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

TABLE 3 Effects of different types of sandstorm hours on winter wheat yield.

Variables	(1)	(2)
Visibility levels		
Less severe sandstorm (200 m ≤ visibility <1000 m)	−0.011*	
	(0.006)	
More severe sandstorm (visibility<200 m)	−0.019**	
	(0.008)	
Crop stages		
Sandstorm in fall		−0.195**
		(0.079)
Sandstorm in winter		−0.087***
		(0.028)
Sandstorm in spring		−0.011***
		(0.004)
Weather controls	Yes	Yes
Year FE	Yes	Yes
County FE	Yes	Yes
R-squared	0.700	0.701
Observations	2224	2224

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. The standard errors shown in parentheses are clustered at county level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

growing season, sandstorms do not have a significant impact on winter wheat yield when lasting less than 4 hours. However, when the duration of sandstorms equals or exceeds four hours, the negative impact becomes significant, and the magnitude of the impact increases with longer durations. Specifically, we find that an additional sandstorm day lasting between four and six hours leads to an 13.5% reduction in wheat yield, while a sandstorm day lasting longer than six hours results in a more substantial reduction of 21.5%.

5.2 | Robustness checks

This section presents the results derived from a series of robustness checks. We put the baseline results in column (1) of Table 4 for reference. First, we replace the year fixed effects in the baseline model with province-year fixed effects. In the baseline model, we assume that the unobserved time-variant factors captured by the year fixed effects affect all countries to the same extent. However, there exist substantial variations in technology, policy, and other external shocks among different provinces. We therefore include province-year fixed effects to capture the effects of unobservable time-varying shocks that are common to the same province. As shown in column (2) of Table 4, the results after controlling for the province-year fixed effects are consistent with the baseline model in column (1).

Second, we adjust the sample coverage by incorporating the locations of sandstorm monitoring stations and modifying the matching radius used to calculate distance-weighted sandstorms. Column (3) in Table 4 presents results based on a subset of 37 sample counties that host sandstorm monitoring stations. In these counties, the effect of sandstorm hours is more pronounced compared to the baseline results, leading to a 2.5% reduction in winter wheat yield for each additional sandstorm

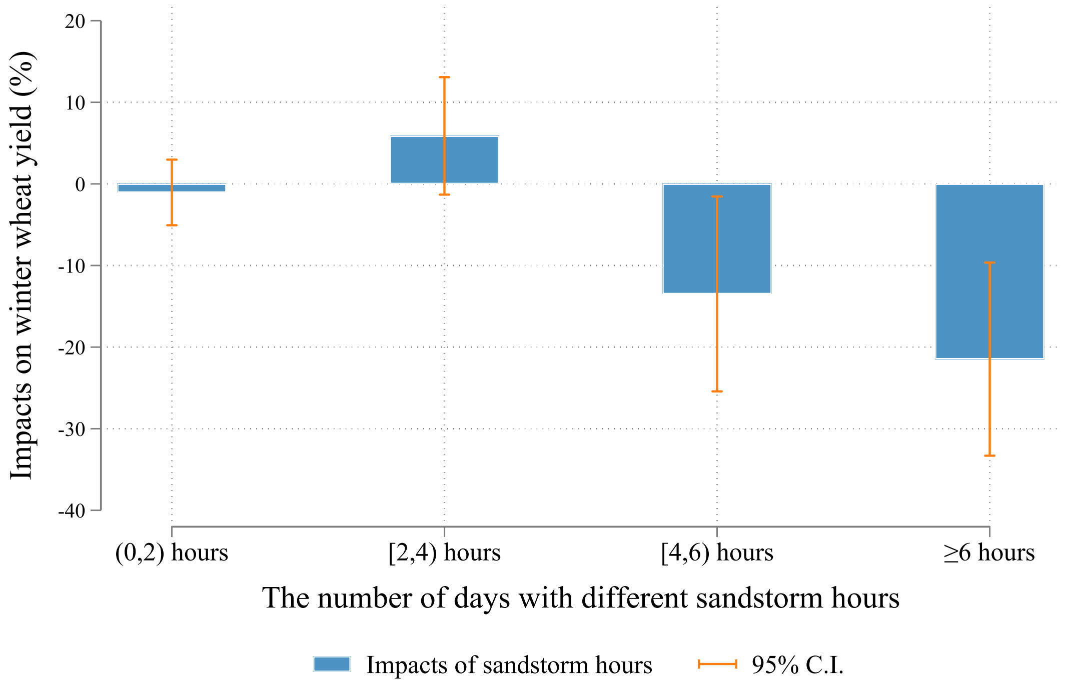

FIGURE 3 Nonlinear impacts of sandstorms on winter wheat yield. The dependent variable is the logarithmic form of the winter wheat yield. Sandstorms are measured by the number of sandstorm days with varying durations. The bars indicate the impact of sandstorm days, and the cap-lines represent the 95% confidence intervals. Coefficient estimates are reported in Table A3.

TABLE 4 Robustness check: Impacts of sandstorm hours.

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Sandstorm hours	−0.014***	−0.014***	−0.025***	−0.012***	−0.015***	−0.014***
	(0.004)	(0.005)	(0.008)	(0.004)	(0.005)	(0.005)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes
PM2.5	No	No	No	No	Yes	No
Year FE	Yes	No	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	No	Yes	No	No	No	No
R-squared	0.700	0.708	0.716	0.699	0.712	0.700
Observations	2224	2224	278	3060	2224	2224

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. Column (1) shows the baseline results in column (1) in Table 2. Column (2) replaces the year fixed effects with the province-year fixed effects. Column (3) and column (4) show the re-estimation results based on the sample counties where the sandstorm monitoring stations are located, and sample counties using 75 km as the matching radius of the sandstorm monitoring stations, respectively. Column (5) reports the results that control for the PM2.5 and use the ventilation coefficient as the instrumental variable. The county-level PM2.5 concentration data are collected from the Atmospheric Composition Analysis Group. The ventilation coefficient data are obtained from the European Centre for Medium-Term Weather Forecasting (ECMWF) ERA-Interim dataset. The standard errors shown in parentheses in columns (1)–(5) are clustered at county level, while standard errors shown in parentheses in column (6) are clustered at the county and city-year levels. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

hour during the growing season. Column (4) reports the coefficient estimates when the matching radius is expanded from 50 km in the baseline model to 75 km. These results remain consistent with our baseline estimates, further reinforcing their robustness.

Third, we estimate the effects of sandstorms after controlling for other potential confounding factors. A key concern is the potential endogeneity of air pollution, which could bias the estimates of the sandstorm impacts. To address this, we follow the literature and use the ventilation coefficient as an instrumental variable for air pollution (Hering & Poncet 2014). Table A4 presents the first-stage results, suggesting that the ventilation coefficient can serve as a valid instrumental variable. The results in column (5), which incorporate the effects of PM2.5, align closely with those in column (1), where PM2.5 concentrations are not controlled, indicating the robustness of the estimated sandstorm effects.

Fourth, we use a two-way clustering strategy to address concerns about the potential spatial and serial correlations in the error term. When clustering standard errors by county, we assume that the standard errors are serially correlated over the years within each county. However, the error terms may also exhibit both spatial and temporal correlations, as well as heteroskedasticity (Auffhammer et al. 2013). To account for these potential correlations, we apply a two-way clustering strategy, where we cluster standard errors at both the county- and city-year levels. This approach allows for serial correlation within counties and spatial correlations among counties within the same prefecture city and year. The results presented in column (6) of Table 4 show that our findings are robust to different clustering specifications of standard errors.

Finally, to assess the robustness of our results over a longer study period, we use an additional dataset covering sandstorm data from 2000 to 2013, as opposed to the baseline period from 2000 to 2007. This dataset, also from CMDC, provides monthly sandstorm days for 127 counties over the extended period. Although this dataset includes fewer counties, it offers a longer time span. Using sandstorm days as the measure, we re-estimate the baseline model. The results, presented in column (2) of Table A5, show that the sandstorm impacts on wheat yield using the extended dataset are consistent with those from the baseline model in column (1), though the magnitude of the effect is slightly larger for sandstorm occurrence.

In addition to using sandstorm hours as the primary explanatory variable, we also run robustness checks using sandstorm hours categorized by varying visibility and sandstorm hours across different crop stages. The results, presented in Table A6, remain consistent with our baseline findings.

6 | MECHANISM ANALYSIS

This section presents the empirical findings on how farmers adapt to the impacts of sandstorms. We begin by estimating how farmers adjust their planted area in response to sandstorms, using household-level data. Next, we quantify the role of agricultural inputs in mitigating the adverse effects of sandstorms on crop yields. Finally, we explore the role of irrigation access in alleviating yield loss caused by sandstorms.

6.1 | Adjusting planted area to mitigate losses from sandstorms

The results in Section 5 highlight the significant negative impact of sandstorms on winter wheat yields. A key follow-up question is how sandstorms affect food security, particularly in terms of changes to the planted area. One hypothesis is that farmers may reduce the planted area as a strategy to mitigate the adverse effects of sandstorms. In the study area, winter wheat is typically planted in October and harvested in late May or early June of the following year. During this period, no other crops are cultivated due to the cold winter conditions.

To test this hypothesis, we use detailed farm-level panel data and apply a two-way fixed effects model, as specified in Equation (3). The results are presented in Table 5. Column (1) shows that sandstorm occurrences in the previous year led to a 1.1% reduction in the winter wheat planted area in the current year, compared to years without sandstorms. In column (2), we examine the effects of sandstorm intensity, finding that each additional hour of sandstorm duration in the previous year leads to a 0.2% decrease in the winter wheat planted area. This reduction may reflect farmers' anticipation of recurring sandstorms, prompting them to reduce the planted area to mitigate potential future losses.

We also investigate the impact of sandstorms occurring during the current growing season on the planted area of winter wheat. Since planting decisions are made before sandstorms typically occur, we hypothesize that sandstorms in the current year will not influence the crop planted area. Columns (3) and (4) in Table 5 support this hypothesis, as the coefficients for the sandstorm variables are statistically insignificant.

6.2 | Adaptation effects of agricultural inputs

Given the vulnerability of crops to sandstorm impacts, it is crucial to understand how specific adaptation measures can mitigate these adverse effects on wheat production. We further examine the adaptive effects of various agricultural inputs. Using farm-level panel data, we analyze the impacts of four key inputs including seed, fertilizer, labor, and machinery.

We first examine whether sandstorms influence agricultural inputs using Equation (3). The results presented in Table 6 indicate that sandstorm occurrences during the winter wheat growing season are associated with increases in certain agricultural inputs. Specifically, after controlling for province-year and household fixed effects, sandstorm occurrences are associated with a 12.7% increase in fertilizer costs (Col. (1) in Panel A) and an 8.0% increase in labor days (Col. (2) in Panel

TABLE 5 The impact of sandstorms on winter wheat planted area at the household level.

	Ln (planted area)			
Variables	**(1)**	**(2)**	**(3)**	**(4)**
Sandstorm occurrence in previous year	−0.011** (0.005)			
Sandstorm hours in previous year		−0.002*** (0.001)		
Sandstorm occurrence in current growing season			0.004 (0.004)	
Sandstorm hours in current growing season				0.002 (0.003)
Weather controls	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes
Province-Year FE	Yes	Yes	Yes	Yes
Household-FE	Yes	Yes	Yes	Yes
R-squared	0.922	0.923	0.921	0.921
Observations	4988	4988	4988	4988

Note: The county-level weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure over growing season, respectively. Other controls include county-level total planted area of winter wheat, household-level total planted area of grain crops and arable land area. The standard errors shown in parentheses are clustered at household level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

A), compared to periods without sandstorms. When sandstorm intensity is considered, the results remain consistent, with each additional hour of sandstorm exposure associated with an 11.3% increase in per-hectare fertilizer costs (Col. (1) in Panel B) and a 10.3% increase in per-hectare labor days (Col. (2) in Panel B). In contrast, columns (3) and (4) show that sandstorm occurrence and duration have no significant effects on seed and machinery costs for winter wheat.

Next, we quantify the moderating effects of agricultural inputs on the impacts of sandstorms. The marginal adaptation effects of these inputs are estimated using interaction terms between sandstorm hours and input quantities in Equation (4), which captures how increases in the corresponding inputs help mitigate yield losses caused by sandstorms. We examine two specifications: One where each input is entered separately (Cols. (1)–(4) in Table 7), and another where all inputs are included in the same regression (Col. (5) in Table 7).

Table 7 shows that increases in fertilizer and labor inputs are significantly associated with substantial reductions in crop yield losses caused by sandstorms. As shown in column (1), a 1% increase in per-hectare fertilizer costs leads to a 5.4% reduction in the negative impact of sandstorm hours on yields. This effect likely arises from the ability of additional fertilizer to quickly replenish soil nutrients lost during sandstorms and to address nutrient deficiencies caused by dust accumulation on plants. Similarly, column (2) indicates a 1% increase in labor days reduces yield losses by 15.8%, highlighting the critical role of manual labor in mitigating sandstorm impacts. Manual activities such as dust removal from leaves and stabilizing damaged crops promote recovery and minimize further losses. These findings are consistent with practical observations that farmers often respond to sandstorms by applying additional fertilizer and manually cleaning crop foliage (Middleton 2024b). In contrast, columns (3) and (4) reveal that farmers did not increase spending on seeds or machinery as part of their response to mitigate sandstorm events.

TABLE 6 The impacts of sandstorms on production inputs at household level.

Variables	Ln (fertilizer cost) (1)	Ln (labor days) (2)	Ln (seed cost) (3)	Ln (machinery cost) (4)
Panel A: Impacts of sandstorm occurrence				
Sandstorm occurrence	0.127***	0.080***	−0.012	0.026
	(0.046)	(0.028)	(0.010)	(0.026)
R-squared	0.683	0.846	0.277	0.821
Observations	4980	4456	4988	4401
Panel B: Impacts of sandstorm hours				
Sandstorm hours	0.113***	0.103***	−0.005	0.035
	(0.033)	(0.013)	(0.006)	(0.022)
R-squared	0.685	0.848	0.277	0.822
Observations	4980	4456	4988	4401
Control variables in Panel A and Panel B				
Weather controls	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes
Province-Year FE	Yes	Yes	Yes	Yes
Household- FE	Yes	Yes	Yes	Yes

Note: The dependent variable is the logarithm of the per unit area production inputs of winter wheat. The county-level weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure over growing season, respectively. Other controls include county-level total planted area of winter wheat, household-level total planted area of grain crops and arable land area. The standard errors shown in parentheses are clustered at household level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

TABLE 7 The moderating effects of production inputs on the impacts of sandstorms on winter wheat yield.

	(1)	(2)	(3)	(4)	(5)
Sandstorm hours	−0.389***	−0.831***	−0.031***	−0.179**	−0.687***
	(0.095)	(0.169)	(0.011)	(0.082)	(0.152)
Sandstorm hours ×Ln (Fertilizer cost)	0.054***				0.038**
	(0.014)				(0.018)
Sandstorm hours ×Ln (Labor days)		0.158***			0.062*
		(0.033)			(0.037)
Sandstorm hours ×Ln (Seed cost)			0.001		0.001
			(0.001)		(0.001)
Sandstorm hours ×Ln (Machinery cost)				0.021	0.012
				(0.013)	(0.010)
Weather controls	Yes	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes	Yes
Province-Year FE	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes
R-squared	0.861	0.870	0.861	0.887	0.894
Observations	4980	4456	4988	4401	3982

Note: The dependent variable is the logarithm of winter wheat yield. The county-level weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure over growing season, respectively. Other controls include county-level total planted area of winter wheat, household-level total planted area of grain crops and arable land area. The standard errors shown in parentheses are clustered at household level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

6.3 | The washing effect: The role of irrigation

Field experiments have shown that the accumulation of sand on crops is a key pathway through which sandstorms reduce crop yields (Giltrap et al. 2021), in addition to causing direct damage to plants (Duniway et al. 2019). Agronomists suggest that timely precipitation and irrigation can mitigate these adverse effects by removing dust from crop surfaces and improving soil moisture levels (Ahmadzai 2023; Nordstrom & Hotta 2004). Irrigation, in particular, can wash away sand and soil particles that adhere to crop surfaces, alleviating the drought conditions that often follow sandstorms (Glotter & Elliott 2016). Despite these theoretical predictions, the precise extent of the "washing effect" of irrigation on agricultural productivity remains unclear. Therefore, this study aims to quantify the potential washing effect of irrigation on farmland, using county-level data to assess its impact.

To evaluate the washing effects of irrigation, we incorporate interaction terms between sandstorm hours and the irrigation ratio in the county-level baseline model. The results in column (1) of Table 8 indicate that favorable irrigation conditions help mitigate the negative impacts of sandstorms on agricultural production, as evidenced by the significant positive coefficient of the interaction term. Specifically, with the same number of sandstorm hours, a 1-percentage-point increase in the irrigation ratio would reduce the negative impact of sandstorms on winter wheat yield by 1.6%.

Furthermore, we examine the washing effect of irrigation on sandstorm impacts under different precipitation conditions. Precipitation, as a natural phenomenon, can effectively wash away dust from crop surfaces and improve soil moisture conditions. This raises the question of whether irrigation still has a washing effect in regions with ample precipitation. We compare the extent to which irrigation mitigates the negative impacts of sandstorms across sample counties with varying precipitation levels. Specifically, we calculate the average precipitation for each sample county over the

TABLE 8 Washing effects: The role of irrigation at county level.

Variables	Ln (yield) Full sample (1)	Less precipitation (2)	More precipitation (3)
Sandstorm hours	−0.020***	−0.017***	−0.030
	(0.005)	(0.005)	(0.038)
Sandstorm hours × irrigation ratio	0.016*	0.021***	0.056
	(0.009)	(0.007)	(0.114)
Irrigation ratio	0.222*	0.170	0.322***
	(0.118)	(0.252)	(0.113)
Weather controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
R-squared	2214	1107	1107
Observations	0.698	0.732	0.690

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. The standard errors shown in parentheses are clustered at household level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

study period and categorize them as more- or less-precipitation regions using the median. We then assess the washing effects of irrigation in these two groups by including an interaction term between irrigation ratio and sandstorms in the model. As shown in columns (2) and (3) of Table 8, adequate and timely irrigation effectively mitigates yield losses associated with sandstorms in counties with less precipitation. In areas with abundant rainfall, precipitation acts as a natural dust washer, such that sandstorms do not significantly impact winter wheat yields, and the washing effect of irrigation becomes insignificant.

7 | DISCUSSIONS AND CONCLUSIONS

This study provides empirical evidence on the effects of sandstorms on crop yields, using a comprehensive county-level panel dataset. By analyzing data from 288 counties in China's primary winter wheat production region between 2000 and 2007, we find a substantial reduction in winter wheat yield in northern China due to sandstorms. Specifically, compared to years without sandstorms, the occurrence of sandstorms during the growing season led to a significant reduction of 14.8% in winter wheat yield. Our estimates uniquely isolate the effects of dust storms on crop growth, filling a gap in the literature where previous studies have largely focused on climate change and air pollution, without addressing sandstorms specifically. Remarkably, this yield loss is comparable to the impact of a typhoon, which typically causes yield reductions of 17% to 20% (Cai et al. 2021), and exceeds the direct damage caused by hurricanes, which result in a 9.2% yield reduction (Spencer & Polachek 2015). Furthermore, the magnitude of sandstorm-induced yield losses aligns closely with the anticipated 14% decline in winter wheat yield from 2021 to 2050 due to climate change under the RCP8.5 emissions scenario (Yang et al. 2019). In terms of ozone pollution—another major factor impacting wheat yields—the damage caused by sandstorms is similar to the projected wheat yield losses in China due to ozone pollution by 2030, which are estimated at an average of 14.7% (Avnery et al. 2011).

In addition to highlighting the significant impact of sandstorms on agricultural production, our study offers two key policy implications. First, our detailed measurement of sandstorms provides a more accurate tool for predicting crop yield losses, essential for short-term food security planning. Our findings show that each additional hour of sandstorm exposure during the winter wheat growing season results in a 1.4% yield reduction, or about 60 kg per hectare. We also observe that sandstorm severity, measured by visibility levels, influences yield loss: Each additional hour of less severe sandstorms decreases yield by 1.1%, while more severe sandstorms lead to a 1.9% decrease. Importantly, the negative impact on winter wheat growth becomes noticeable only after sandstorm durations exceed four hours. Furthermore, we find that winter wheat is most sensitive to sandstorms during the fall and winter seasons. In response, farmers may reduce the planted area, as evidenced by a 1.1% decrease in winter wheat area after sandstorms in the previous year. These estimates offer a valuable basis for assessing the economic losses caused by sandstorms in agriculture.

Secondly, building on existing literature that evaluates *ex-ante* source control measures (Jiang et al. 2018; Tan & Li 2015), our study emphasizes the importance of *ex-post* strategies to mitigate sandstorm impacts. While source control is crucial for minimizing long-term sandstorm effects, *ex-post* measures become particularly essential after sandstorms have occurred. Our findings show that winter wheat yield losses due to sandstorms can be effectively mitigated by increasing fertilizer use and labor days following these events. This highlights the importance of timely postdisaster guidance, advising farmers to boost production inputs to reduce losses. Additionally, our research suggests that the negative impacts of sandstorms on winter wheat yields are less severe in regions with robust irrigation systems, especially in areas with low precipitation, which indicates that when post-sandstorm rainfall is insufficient, prompt irrigation can help mitigate adverse effects. These results provide valuable insights for policymakers and agricultural stakeholders, emphasizing the need for effective *ex-post* strategies as part of broader sandstorm management efforts.

ACKNOWLEDGMENTS

This work acknowledges the financial support of the National Natural Science Foundation of China (Grant no. 72322008, 72173004, 72348003 and 41971130). We also express our gratitude to the three anonymous reviewers for their insightful comments and to Jesse Tack for serving as editor.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Du, Jue, Lingling Hou, Yuanyuan Zhao, and Zhexi Zhang. 2025. "Impacts of Sandstorms on Wheat Yield in Northern China." *American Journal of Agricultural Economics* 107(4): 1087–1116. https://doi.org/10.1111/ajae.12532

APPENDIX A

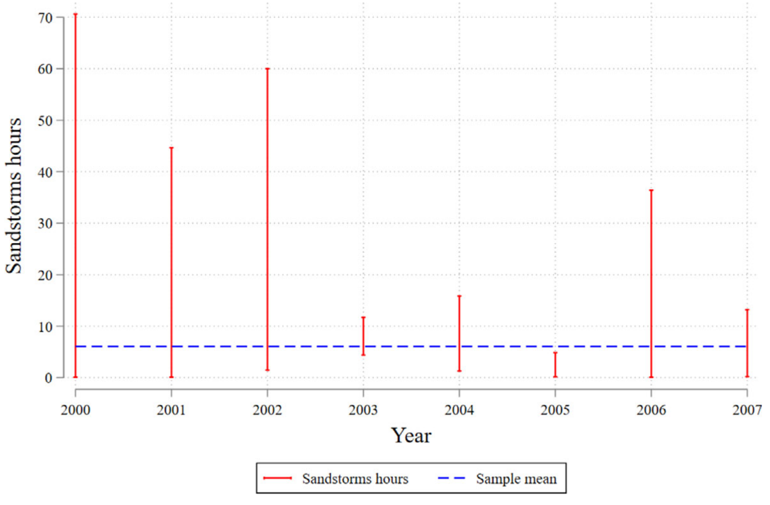

FIGURE A1 Trends in the number of sandstorm hours in sample counties with sandstorms. The solid line represents the annual range of sandstorm hours across the sample counties, while the dotted line depicts the average sandstorm hours from 2000 to 2007. Sandstorm hours are calculated as the cumulative duration of sandstorms during the winter wheat growing season in the sample counties.

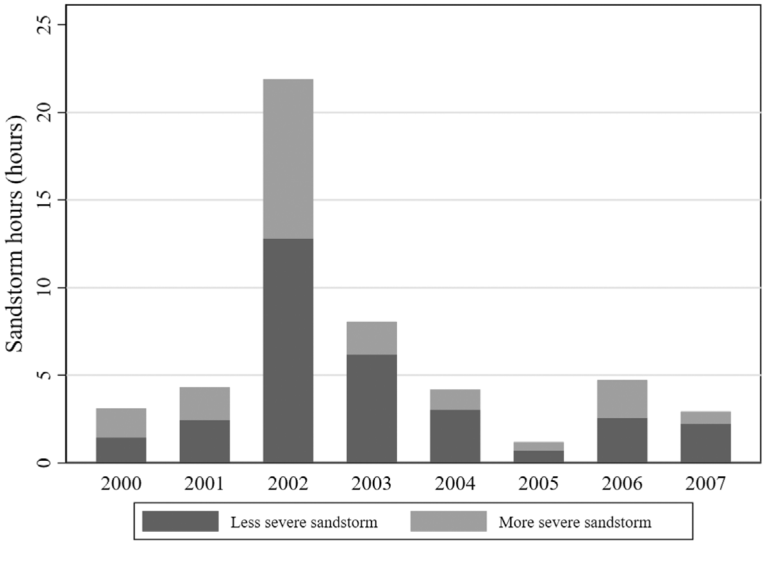

FIGURE A2 The distribution of sandstorm hours at different visibility levels in sample counties. The figure is based on data from sandstorm monitoring stations in sample counties. Less severe sandstorms are defined as the sandstorms that have visibility equal to or greater than 200 m, while more severe sandstorms are defined as the those with visibility less than 200 m.

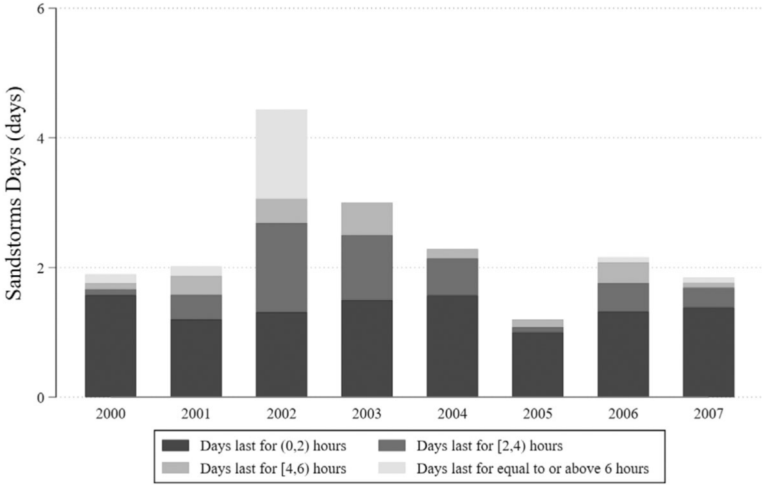

FIGURE A3 Proportion of sandstorm days with different durations hours in sample counties. The figure is based on data from sandstorm monitoring stations in sample counties. Each bar indicates the average proportion of sandstorm days with varying durations relative to the total number of sandstorm days during the winter wheat growing season.

TABLE A1 Summary statistics of weather variables.

Variable	Unit	Mean	Std	Min	Max
Sandstorm hours in fall	hours	0.00	0.06	0.00	2.67
Sandstorm hours in winter	hours	0.03	0.47	0.00	15.36
Sandstorm hours in spring	hours	0.46	3.33	0.00	63.44
Sandstorm days in growth season	days	0.22	1.00	0.00	17.00
Sandstorm days last for 1–2 h	days	0.14	0.58	0.00	8.00
Sandstorm days last for 3–4 h	days	0.04	0.31	0.00	6.00
Sandstorm days last for 4–6 h	days	0.02	0.18	0.00	3.00
Sandstorm days last for more than 6 h	days	0.02	0.24	0.00	5.00
Average wind speed					
Fall	m/s	1.98	0.58	0.77	7.47
Winter	m/s	2.16	0.61	0.78	7.35
Spring	m/s	2.73	0.62	1.19	7.93
GDD_{low}					
Fall	degree days	501.14	57.97	216.25	593.67
Winter	degree days	168.47	82.04	0.31	405.50
Spring	degree days	931.97	49.43	665.95	1005.03
GDD_{med}					
Fall	degree days	187.62	50.70	42.66	319.76
Winter	degree days	6.48	7.59	0.00	41.03
Spring	degree days	471.39	54.11	220.09	559.67
GDD_{high}					
Fall	degree days	57.38	31.60	0.01	169.04
Winter	degree days	0.06	0.22	0.00	3.30

TABLE A1 (Continued)

Variable	Unit	Mean	Std	Min	Max
Spring	degree days	324.85	77.21	31.97	514.12
Accumulative precipitation					
Fall	cm	7.40	5.47	0.05	30.21
Winter	cm	2.15	1.47	0.16	12.55
Spring	cm	10.59	4.35	1.72	29.99
Accumulative sunshine hours					
Fall	100 h	345.85	64.89	96.94	510.41
Winter	100 h	463.79	70.01	225.00	668.90
Spring	100 h	787.23	78.35	410.54	983.69
Average relative humidity					
Fall	%	66.48	6.84	42.19	84.52
Winter	%	59.32	5.67	39.78	77.13
Spring	%	51.59	6.98	32.47	69.94
Average air pressure					
Fall	kPa	973.80	45.65	861.99	1022.58
Winter	kPa	977.74	47.74	861.26	1028.22
Spring	kPa	964.92	44.85	856.04	1013.13

Note: The summary statistics are from a total of 2224 observations that cover 288 counties across 4 provinces from 2000 to 2007. The sub-seasons define as fall (Sowing to November), winter (December to February) and spring (March to Harvest).

TABLE A2 The impacts of sandstorm days on winter wheat yield.

Variables	(1)	(2)
Sandstorm days	−0.044**	−0.043**
	(0.020)	(0.020)
Weather controls	No	Yes
Year FE	Yes	Yes
County FE	Yes	Yes
R-squared	0.681	0.699
Observations	2224	2224

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. The standard errors shown in parentheses are clustered by county level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

TABLE A3 Nonlinear impacts of sandstorm on winter wheat yield.

Variables	**(1)**
Sandstorm days last for (0, 2) hours	−0.010
	(0.021)
Sandstorm days last for [2, 4) hours	0.059
	(0.037)
Sandstorm days last for [4, 6) hours	−0.135**
	(0.061)
Sandstorm days last for more than 6 hours	−0.215***
	(0.060)
Weather controls	Yes
Year FE	Yes
County FE	Yes
R-squared	0.698
Observations	2224

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. The standard errors shown in parentheses are clustered by county level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

TABLE A4 The first-stage results of instrumental variable analysis for PM2.5.

Variables	**(1)**
Ventilation coefficient	−0.016***
	(0.003)
Kleibergen-Paap Wald rk LM statistic	$P < 0.001$
Cragg-Donald Wald F statistic	66.92
Kleibergen-Paap rk Wald F statistic	34.49
Weather controls	Yes
Year FE	Yes
County FE	Yes
Observations	2224

Note: The dependent variable is PM2.5 concentration. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. The standard errors shown in parentheses are clustered by county level, with * indicating $p < 0.05$, ** indicating $p < 0.01$, and *** indicating $p < 0.001$.

TABLE A5 Robustness check: use long period sample.

Variables	**(1)**	**(2)**
Panel A. The impacts of sandstorm occurrence		
Sandstorm occurrence	−0.148***	−0.169**
	(0.042)	(0.083)
R-squared	0.700	0.827
Observations	2224	1654
Panel B. The impacts of sandstorm days		
Sandstorm days	−0.043**	−0.039**
	(0.020)	(0.017)
R-squared	0.700	0.827
Observations	2224	1654
Control variables in Panel A and Panel B		
Weather controls	Yes	Yes
Year FE	Yes	Yes
County FE	Yes	Yes

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. Column (1) shows the baseline results in Column (2) of Table 2 and Table A3, and Column (2) uses the long-period monthly sandstorm data covering 149 counties from 2000 to 2013. The standard errors shown in parentheses in are clustered at county level. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE A6 Robustness check: impacts of sandstorm hours at different visibility and different crop stages.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. The impacts of sandstorm hours with different visibility						
Common sandstorm	−0.011*	−0.009	−0.005	−0.013**	−0.012*	−0.011*
	(0.006)	(0.006)	(0.012)	(0.005)	(0.007)	(0.006)
Severe sandstorm	−0.019**	−0.022***	−0.056***	−0.014*	−0.021***	−0.019**
	(0.008)	(0.008)	(0.020)	(0.008)	(0.008)	(0.010)
R-squared	0.700	0.708	0.722	0.699	0.712	0.700
Observations	2224	2224	278	3060	2224	2224
Panel B. The impacts of sandstorm hours in different crop stages						
Sandstorm hours in fall	−0.195**	−0.205**	−0.131	−0.153**	−0.197**	−0.195*
	(0.079)	(0.091)	(0.086)	(0.070)	(0.086)	(0.105)
Sandstorm hours in winter	−0.087***	−0.090***	−0.157***	−0.062***	−0.087***	−0.087***
	(0.028)	(0.033)	(0.021)	(0.023)	(0.033)	(0.027)
Sandstorm hours in spring	−0.011***	−0.011***	−0.020**	−0.010***	−0.012***	−0.011***
	(0.004)	(0.004)	(0.007)	(0.004)	(0.005)	(0.003)
R-squared	0.701	0.709	0.723	0.699	0.712	0.701
Observations	2224	2224	278	3060	2224	2224
Control variables in Panel A and Panel B						
$PM_{2.5}$	No	No	No	No	Yes	No
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	No	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Province-year FE	No	Yes	No	No	No	No

Note: The dependent variable is the logarithm of winter wheat yield. The weather control variables include average wind speed, GDD_{low}, GDD_{med}, GDD_{high}, accumulated precipitation, accumulated sunshine hours, average relative humidity and average air pressure in fall, winter and spring, respectively. Column (1) shows the baseline results in column (1) in Table 2. Column (2) replaces the year fixed effects with the province-year fixed effects. Column (3) and column (4) show the re-estimation results based on the sample counties where the sandstorm monitoring stations are located, and sample counties using 75 km as the matching radius of the sandstorm monitoring stations, respectively. Column (5) reports the results that control for the PM2.5 and use the ventilation coefficient as the instrumental variable. The county-level PM2.5 concentration data are collected from the Atmospheric Composition Analysis Group. The ventilation coefficient data are obtained from the European Centre for Medium-Term Weather Forecasting (ECMWF) ERA-Interim dataset. The standard errors shown in parentheses in columns (1)–(5) are clustered at county level, while standard errors shown in parentheses in column (6) are clustered at the county and city-year levels. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.